Task-based optimal design of serial metamorphic manipulators.

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***Abstract*— In this paper the key issues for task based optimal design of metamorphic serial manipulators is presented. The key elements, indices as well methods for solving the optimization problem are presented. Finally, conclusions and future research directions are presented.**

I. Introduction

The designer of a robotic manufacturing workcell, has to address several key issues, such as the matching of the robot's anatomy to the envisaged task(s), the optimal placement of the task(s) in the robot's workspace so as to achieve the best robot performance during execution, the optimal sequencing of the task(s) so as to achieve shorter cycle times, etc. These considerations are task oriented, resulting in the design of a robotic workcell with optimal performance for a number of specific tasks. However, due to this approach there is no guarantee that the derived workcell design will be able to achieve the same high performance standards, should it be used to execute tasks that are entirely different from which it was designed for.

In the last decades, the reconfiguration paradigm was identified as a key feature for the enhancement of the manufacturing productivity [1], thus research efforts in robotics took a turn towards the design and application of reconfigurable robots. The reconfigurable robots are structured by self-contained modules where the user is able to change the anatomy of an existing structure by rearranging them. Due to their adaptability, reconfigurable robots are ideal for usage in SME's, where small batches of different products are usually manufactured according to market needs, and therefore a wider variety of robotic tasks is to be addressed as opposed to dedicated large batch production facilities. Should fixed anatomy robots were to be used in SME's, a substantial investment would be required, something impossible for such companies.

Designing a robotic workcell including reconfigurable robots is a far more challenging task than the design of a typical fixed anatomy robot workcell, since the synthesis of different anatomies for this class of manipulators is an ongoing process, as for every different task, a new anatomy should be derived for the highest robot performance.

Metamorphic robots have been proposed in the relevant literature for their ability to alter their anatomy in order to meet the demands of different tasks. The proposed class addressed the limitations of current fixed anatomy manipulators in performing different types of tasks. Additionally since a metamorphic structure can be altered to obtain a significant number of different anatomies via the offline variation of connecting modules contained therein, the proposed class also addressed the main drawback of modular reconfigurable manipulators were a given structure has to be partially or totally dismantled and reassembled to a new anatomy best matching a different task type. The transition between different anatomies is achieved via the off-line manual resetting of variable connective modules called "pseudojoints". The manual selection was selected over an active self-contained joint that could provide self-reconfiguration capabilities in order to provide a robotic system of higher robustness and reduced complexity and cost, as opposed to a self-reconfigurable manipulator that would retain the aspect of metamorphosis and therefore being capable of performing a wider variety of tasks.

In this paper, the key issues for task-based design of metamorphic serial modular manipulators will be presented. In the first section, the modular structure of metamorphic robots is presented. In the following, the process as well as the parameters of the task based kinematic design is presented. The structural as well as the kinematic indices used for optimization are described in sections three and four respectively. Problem solving methods and their limitations are presented in section five. Finally, concluding remarks and future research directions concerning task-based design are closing this paper.

II. The metamorphic manipulators

The modular reconfigurable manipulators are built by a variety of basic components. The structure as well as the anatomy alteration is achieved by – partially or in total-dismantling an existing structure or anatomy to its base components and reassembling them to the new one. The modular metamorphic manipulators are introduced as a solution to the requirement of rapid anatomy alteration in a flexible manufacturing system or in areas where the performance of multiple type of tasks is required [2], [3]. They have modular structure, but the transition from one anatomy to another is conducted rapidly and without dismantling the initial robot structure.

Three main types of modules are utilized to structure serial metamorphic manipulators :

- active joints: self-contained modules with 1 dof providing controllable motion to the metamorphic robot.
- pseudo joints: passive connection modules with 1 dof, for structuring and anatomical alteration of serial metamorphic manipulators.
- rigid links: for connecting the various modules of the metamorphic robot.

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An example of a metamorphic mechanism structured as such is illustrated in fig. 1 along with the process of its metamorphosis from its initial form to a required one. The mechanism consists of two active rotational joints, two rigid links and two pseudo joints which will facilitate its rapid reconfiguration. In fig. 1(a), the mechanism is shown at its reference anatomy, where all pseudo joints in the robot's lattice are considered to be at their starting configuration where their angles are set to 0^0. Therefore in fig. 1(a) the pseudo joint angles are $\theta_a=\theta_b=0^0$. In this reference anatomy the twists of the active joints ξ_1 and ξ_2 are parallel.

The reconfiguration to the desired anatomy is achieved via the subsequent rotation required about each of the two inserted twists ξ_a and ξ_b (figures 1(b) and 1(c)). The reconfiguration is conducted by first rotating pseudo joint b by 90^0, which results in the anatomy depicted in fig. 1(b), where the pseudo joint angles are $\theta_a=0^0$ and $\theta_b=90^0$. Next pseudo joint a is rotated to $\theta_a=90^0$ so the mechanism is transformed to the desired anatomy fig. 1(c) where the pseudo joint angles are $\theta_a=\theta_b=90^0$. In the new metamorphosed anatomy the twists of the pseudo joints are perpendicular, while also the relative lengths of the mechanism have changed. Pseudo joints also allow the operator to achieve anatomies of a metamorphic manipulator that are not currently favored in robotic design, i.e. in D-H representation presenting link twists different to the standard 0^0 or 90^0 of current robotic systems or in screw representation consecutive joint twists being either parallel or perpendicular. The link twist is the angle between two successive joint axes (joint twists) if these are projected on a plane whose normal coincides with the mutual perpendicular to the successive joint twists.

During the design phase of metamorphic workcells the key issues to be addressed are, the determination of the degrees of freedom of the robot which are defined by the active joints, the structure (topology) of the metamorphic robot, taking into account the type of the joints and the number of pseudo joints, the optimal anatomy of the metamorphic robot for the highest possible task execution performance and the optimal placement of the task in the workspace of the metamorphic robot.

III. TASK-BASED KINEMATIC DESIGN OF METAMORPHIC MANIPULATORS.

The design problem can be stated as follows: *Given a specific kinematic task or group of kinematic tasks synthesize the optimal structure of a metamorphic manipulator and determine the optimal anatomy and task location in the metamorphic manipulator's workspace for task execution with the highest possible performance*.

The design parameters of this problem are the following:

- The number of dof (number of the active joints) (n).
- The number of the pseudo joints (p).
- The succession of the active joints and pseudo joints in the serial chain
- The relative position and orientation between the axis of the consecutive active joints and pseudo joints.
- The optimal anatomy of the serial metamorphic manipulator defined by the parameters $\theta_{p,j}$ of the (p) pseudojoints for each task.
- The optimal placement of each task in the workspace of the metamorphic robot defined by the variables θ_i of each active joint for a given anatomy.

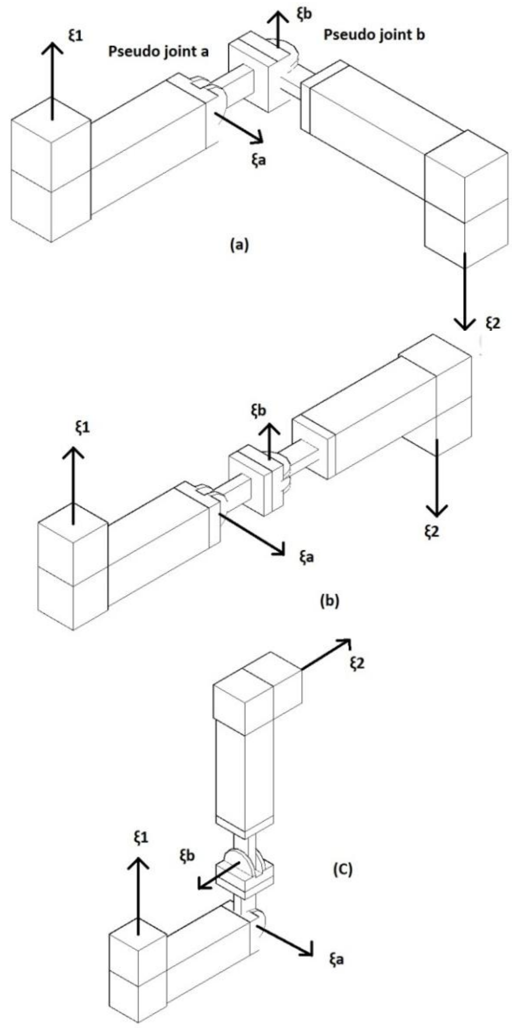

Figure 1. An open kinematic chain with the three main types of modules

In order to design an optimal performing metamorphic robot all these parameters should be taken into account simultaneously. This is a very difficult optimization problem since the design parameters are many and heterogeneous. The type of the universes of discourse of the parameters is either discrete ($\theta_{p,j}$) or continuous (θ_i), while they are also either sets of objects (number and types of modules, succession of modules in the structure chain) or numbers ($\theta_{p,j}$, θ_i). For example, for a metamorphic structure with 3 active joints and 2 passive joints there are three possible combinations for the location of the pseudo joints in the serial kinematic chain, and a lot of combinations for the relative orientation among them. This structure can be represented by objects, while the parameters by numbers.

Simplification of the solving process can be achieved by the following strategy:

- Choose the structural parameters of the metamorphic robot i.e.:
  - Number (n) of degrees of freedom.
  - Number (p) and distribution of pseudo-joints along the structure.
  - Relative position and orientation of axes between the successive joints and pseudo-joints.
- For a given structure, and a chosen task-based kinematic index (*f*) find the optimal anatomy and simultaneously the optimal position of the task in the derived anatomy's workspace:

$$[\underline{\theta}, \underline{\theta}_p]^* = argmax(f(\underline{\theta}, \underline{\theta}_p))) \quad (1)$$

In the following some guidelines and methods towards the solution of this problem are presented.

A. Indices for the selection of the structural parameters.

The number of the active joints is closely related to the tasks under consideration. In the case of multiple tasks the maximum number of active joints should be selected. For example, four active joints are enough for 2-D assembly tasks. However, more complex tasks probably require more than six active joints. The number, the relative position and the orientation of the pseudo joints are closely related with the envisaged required anatomies that the robot should have, so as to perform an expected variety of different tasks. Thus, the position as well as the parameters of the pseudo joints must be adequate in order to allow the metamorphosis of the anatomy of the metamorphic robot per task performance requirements. In addition, two criteria are introduced for the selection of the structural parameters [4]:

- Simplicity of a structure; simplicity is subject to the number of modules used to form a structure. Most importantly the maximum number of pseudo joints is sought to be placed in a link, so as the maximum number of possible relations for the active joint twists connected will be presented.
- Solvability of kinematics; the relative position and orientation of the joints should lead to anatomies whose kinematics are analytically solvable.

The Assembly Incidence Matrix (AIM) was used for the optimal design of a modular robot satisfying particular task requirements based on the minimal degrees of freedom approach. The objective function was defined as the weighted sum of the score of different types of modules in the AIM, while task related kinematic measures were used as design constraints [5].

Using expert knowledge and those indices a structure for all tasks can be defined. In the next phase the optimization of the structure for every task is taken place.

B. Indices for the anatomical parameters and the position of the task.

A methodology was presented in [6] for the optimization of the anatomy of a reconfigurable robotic workcell, where the objective function was formulated considering robot performance for a particular task.

The position of the task in the workspace of the metamorphic robot as well as the determination of the anatomical parameters of the pseudo joints can be completed using well known dexterity measures based on the Jacobian matrix [7].

These indices are based on local kinematic measures such as the manipulability index and the inverse condition number or global such as the global conditioning index (GCI). In fact, any local measure can be integrated across the manipulator's workspace so as to obtain global measures [8], [9] .

The manipulability index was used to find the parameters of a metamorphic serial manipulator in a point visiting task presented in [2]. The metamorphic manipulator was subject to optimization in comparison with a fixed anatomy manipulator that was optimally placed task-wise and kinematically. The optimization was performed so as to find the best anatomical parameters of the pseudojoints.

Additionally, the Manipulability Velocity Ratio (MVR) has been proposed for task-based optimization for a path-following task [2], [10]. The method used to acquire the optimal parameters of the pseudojoints was the same as the point visiting task.

A global kinematic multi criteria index for the determination of the best anatomy of a reconfigurable robot has been proposed in [11]. The criteria used were the overall mean value of the measure, the mean value of the m highest values achieved by the metamorphic robot as well as the distance of the highest value to the mean. The criteria was aggregated using the discrete Choquet integral in order to favor the anatomies that present high values of the kinematic measure with low deviation.

In addition, qualitative and quantitative data of the workspace formed by a single anatomy of a metamorphic robot, such as the volume or the shape of the volume where a local kinematic index is higher than a limit can be used to place the task accordingly.

IV. Problem Solving Methods

The heterogeneity of the parameters and the complexity of the problem to be solved make the conventional optimization methods practically useless. Genetic algorithms, fuzzy logic, neural networks and other heuristics have been used to solve parts of the problem presented. In addition, new representation methods of metamorphic manipulators have been introduced for use with genetic algorithms.

The metamorphic structure representation (MSR) has been proposed for the systematic development and evaluation of structures of metamorphic serial manipulators [4]. MSR provides a representation tool for structuring and evaluating metamorphic serial manipulators.

The rapid global evaluation of predefined metamorphic structures using a multi-criteria index based on the kinematic performance has been presented [11]. An ANFIS system has been trained for the rapid calculation of the proposed global index in order to investigate the dynamic or kinematic performance of any anatomy of the predefined metamorphic manipulator.

Genetic algorithms have been used for the optimization of a point visiting task of a metamorphic manipulator using the manipulability index for the initial position of the task to the workspace of the metamorphic manipulator [2]. The same approach was followed for a path following task using the MVR.

In online methods, such as motion planning in dynamic environments and collision avoidance, the computational complexity must be minimized in order to achieve real-time performance. Motion planning algorithms must calculate the best feasible continuous path in the workspace according to a given metric. When dexterity is the desired metric for optimization, the calculation of the measure has the complexity of formulating the Jacobian of the configuration and calculating the norm of that configuration.

In order to reduce that complexity, an approximation can be used that, although reducing the accuracy, can provide a good enough result at a fraction of the time the analytic calculation would. In [12] a fuzzy approximation was proposed to calculate the Jacobian condition number for a PUMA manipulator, resulting in up to 750% performance improvement. With a proper analysis, any dexterity measure of a kinematic chain can be approximated to the same or even better results. In [13] an ANN was used to approximate the area manipulability measure so as to determine the best docking location for a UUV.

Although the above presented methods can be used in the different phases of task-based design no method has been presented in order to find an optimum solution taking into account all phases of design.

V. CONCLUSIONS - FUTURE DIRECTION OF RESEARCH.

Task based design of metamorphic robots is a complicated problem to be solved. In this paper, the design process as well as key elements that are essential to this problem solving is presented. Design indices for supporting the structuring of a metamorphic manipulator as well as the optimum kinematic design are also presented and discussed.

Future research directions are the following:

- A method for solving the entire problem; although the concept for solving the entire problem has been roughly presented in this paper, a more concrete method must be developed. AI tools will play a significant role, due to the heterogeneity of the problem parameters. In addition, the expert knowledge to task-based design should be incorporated in the system

- Expert knowledge for structuring the metamorphic manipulators; since the universe of discourse of the structures is quite large and some topologies lead to the same anatomical characteristics, expert knowledge can constraint the problem and make the problem solving method easier.

- Use of other heuristic and random-based algorithms which are not commonly used in robotics such as cuckoo search [14].

- Parallel metamorphic manipulators; The representation and methods presented are tested in open-kinematic chains and should be extended to incorporate closed-kinematic chains [15].

- Metamorphosis between open and closed manipulators; Methods should be developed in order to exploit the advantages of both types of mechanisms

- Parallel processing of algorithms; in order to exploit latest advancements in multi-core CPU and GPGPU, optimization algorithms should be designed for parallel computation.

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